Tidal-induced pulses in the flow through the Strait of Gibraltar

Strait of Gibraltar
Satellite data
Aircraft data
Tidal effects
Propagation of fronts

Détroit de Gibraltar
Données de satellite
Données d'avion
Effets de la marée
Propagation de fronts

Paul E. LA VIOLETTE [a], **Henri LACOMBE** [b]

[a] Naval Ocean Research and Development Activity, NSTL, Bay St. Louis, Mississippi, 39529, USA.

[b] Laboratoire d'Océanographie Physique, Muséum National d'Histoire Naturelle, 43 rue Cuvier, 75231 Paris Cedex 05, France.

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ABSTRACT

Ship data collected in the 1960s and recent data from ship, aircraft and satellites indicate that the flow in the Strait of Gibraltar does not move in the form of continuous currents but as tidal-induced pulses. A descriptive model based on these data is presented. The model indicates that the pulses are a result of increases in the speed of the tidal streams as they encounter the constrictions of the regional bathymetry (especially the Camarinal Sill and between the Camarinal Sill and Tarifa). Periodic increases modify the regional flow so that during each tidal cycle, the eastward-flowing surface Atlantic water and westward-flowing deep Mediterranean water are alternately emitted as large pulses into the Mediterranean Sea (Atlantic water) and Atlantic Ocean (Mediterranean water). These periodic pulses vary in the amount of water they contain according to the daily and monthly variation in tidal current strength.

In addition to the pulses generated at the intervals of the semidiurnal tide, it appears that short-period pulses of flow are generated on the Camarinal Sill. Occurring near the time of the greatest local variations of the tidal current, these short-period pulses are able to trigger very strong internal waves and current fronts in the upper layer, which are propagated eastward into the Alboran Sea.

Although there exist non-periodic forces, such as wind and atmospheric pressure, which may cause flow variations, the continuous periodic pulses in the flow described here are a permanent feature of the waters of the Strait of Gibraltar that should be taken into account in any study of the region.

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RÉSUMÉ

Pulsations des flux suscitées par la marée dans le détroit de Gibraltar

Des données collectées par des navires pendant les années 1960 et des données récentes recueillies par des navires, des avions et des satellites montrent que l'écoulement dans le détroit de Gibraltar ne se fait pas de façon continue mais par impulsions sur la période de la marée. Un modèle descriptif fondé sur ces données est présenté. L'importance de ces impulsions résulte du fort accroissement des courants de marée lié à la présence du seuil bathymétrique. Ainsi, durant chaque cycle de marée, le flux superficiel vers l'Est d'eau atlantique et le flux profond vers l'Ouest d'eau méditerranéenne sont alternativement émis sous forme de grandes impulsions vers la Méditerranée (eau atlantique) et vers l'Océan Atlantique (eau méditerranéenne). Ces impulsions périodiques concernent un volume d'eau variant selon l'évolution journalière et mensuelle de la vitesse du courant de marée.

En outre, il apparaît que des pulsations de courte période engendrées sur le seuil, au voisinage du moment des plus grandes variations locales du courant de marée, peuvent susciter des fronts d'ondes internes et de courant dans la couche supérieure : ces fronts peuvent s'y propager vers l'Est et atteindre la Mer d'Alboran.

Quoiqu'il existe d'autres effets agissants susceptibles de provoquer des variations de flux (par exemple : le vent et la pression atmosphérique) les impulsions de flux liées à la marée ici décrites constituent un trait permanent du régime de détroit qui doit être pris en compte dans toute étude de la région.

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GENERAL

As the major point of access of surface water (Atlantic water) entering the highly evaporative Mediterranean Sea, and as an exit channel for high-salinity water (Mediterranean water) flowing at depth into the Atlantic, the Strait of Gibraltar forms a highly variable and complex mechanism of water exchange. Oceanographic events on each side of the strait influence and, in turn, are influenced by the transport through the strait. Yet, because of the complex spatial and temporal variations of the flow, only approximate values of transport are available (Lacombe, Richez, 1982). In order to derive more accurate values, a more realistic understanding of the flow variations in the strait is required.

A great deal of the acquired information on the physical events taking place in the strait has been derived from ship campaigns conducted during the period 1959 through 1967. Analyses of the data from these campaigns are available in numerous reports (*e.g.*, Frassetto, 1964 ; Lacombe *et al.*, 1964 ; Cavanié, 1972 ; Boyce, 1975 ; Lacombe, Richez, 1982 ; 1984 ; Gascard, Richez, 1985).

For technological as well as practical reasons, synoptic observations in the strait are limited. This study merges portions of the ship data with recent ship,

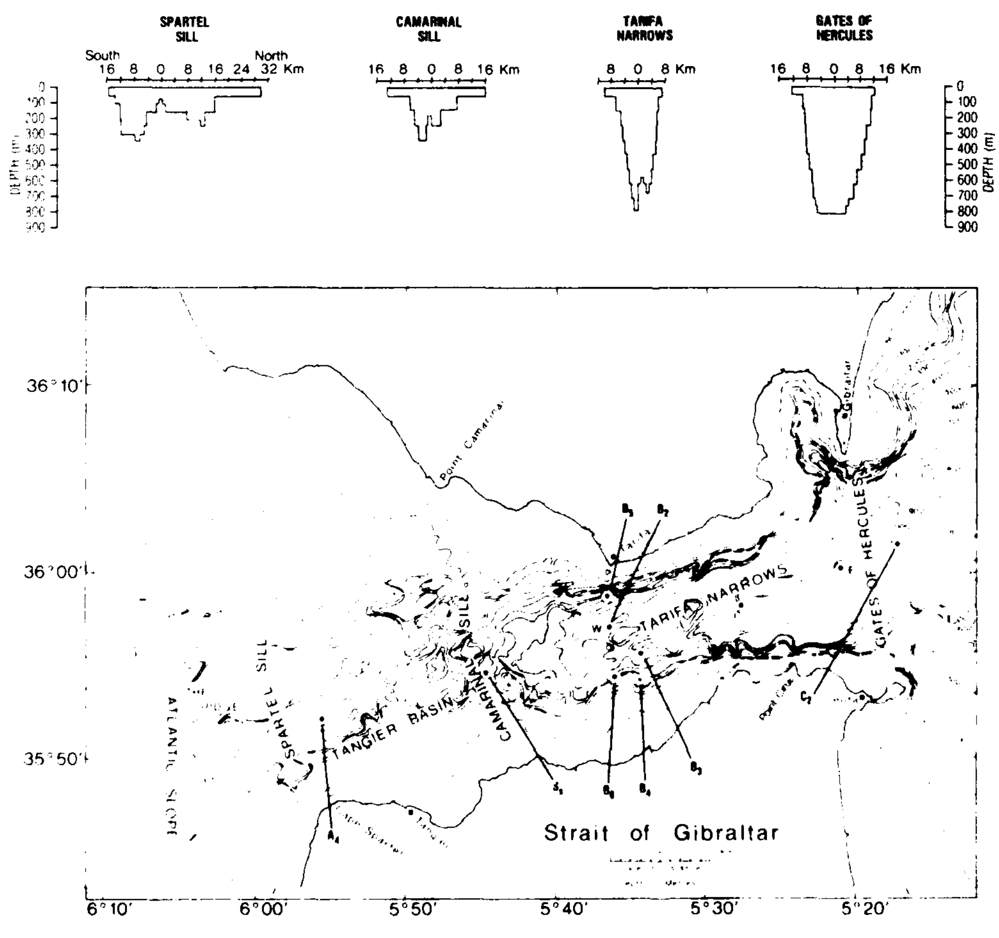

Figure 1

Bathymetry of the Strait of Gibraltar (modified by Armi and Farmer, 1985, from Lacombe and Richez, 1982 and from Giermann, 1961).

Bathymétrie du détroit de Gibraltar (modifié par Armi et Farmer, 1985, d'après Lacombe et Richez 1982 et d'après Giermann, 1961).

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Although there exist non-periodic forces, such as wind and atmospheric pressure, which may cause flow variations, the continuous periodic pulses in the flow described here are a permanent feature of the waters of the Strait of Gibraltar that should be taken into account in any study of the region.

aircraft and satellite data to derive a descriptive model of the flow in the strait. These data have the disadvantages of being scattered in time and, in most cases of short duration. However, the repetition of the events shown in the different data indicates that these events represent normal conditions and can be used to derive a descriptive model of the physical events taking place in the strait.

BATHYMETRY OF THE STRAIT

The bathymetric configuration of the Strait of Gibraltar (Fig. 1) exerts a dominant constriction on the flow of water through the strait. Essentially, the strait is a narrow, fairly steep-sided trough, moderately angled away from an East-West orientation. It has an average depth of some 600 m and varies in width between 20 km at Gibraltar and 14 km at Point Cirus. The distance from Gibraltar at the eastern end of the Strait to Tarifa at the western end is 25 km. Just 13 km west of Tarifa section lies the main bathymetric sill of the strait, the Camarinal Sill, with a maximum depth of slightly more than 300 m. A secondary sill, the Spartel Sill, situated 21 km west of the main sill, has a maximum depth of more than 350 m.

GENERAL FLOW, EXTERNAL AND INTERNAL TIDES AND TIDAL STREAMS

Tidal data

Any examination of oceanic events in the Strait of Gibraltar discloses a heavy tidal influence. Figure 2 shows variations in tidal height for two places in the strait (Tarifa and Ceuta) that are representative of the changes that can be expected. Note that there is little difference in the times of the tide at the western and eastern portions of the strait. For the purposes of this study, therefore, the tide may be considered to occur as a simultaneous event in the strait.

Figure 2 also shows the variations in tidal height that may be expected from spring to neap phases of the tide. Although the tidal height in the strait is predominantly semidiurnal (the form number $F = (K_1 + O_1)/(M_2 + S_2) = 0.08$, Defant, 1961), tide station data show there is a significant diurnal effect.

General flow

It is well known that the general flow in the strait of Gibraltar consists of the superposition of a mean flow and the predominantly semidiurnal tidal flow. The mean inflow of Atlantic water (*i.e.* towards the Mediterranean) and the mean outflow of Mediterranean water (*i.e.* toward the Atlantic) are modulated by an approximately barotropic tidal current (despite the unexpectedly high amplitude of the internal tide). These components are strongly affected by the bathymetric constrictions (the smaller the cross section, the higher the velocity) and the phase of the local internal tide.

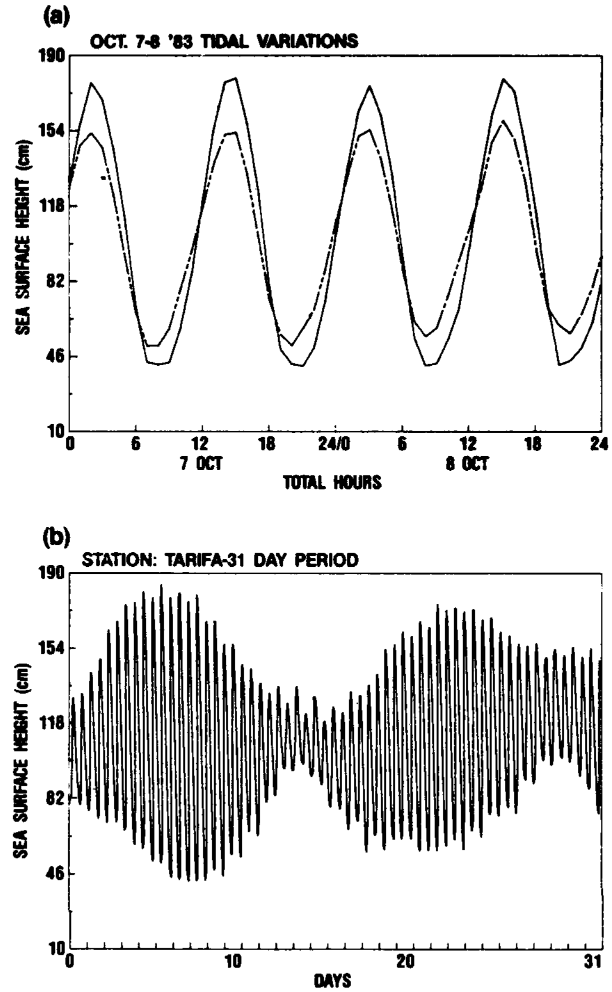


Figure 2

Hourly tide-height variations for (a) forty-eight hours for Tarifa (solid line) and Ceuta (dashed line) and for (b) a 31-day period for Tarifa (tide observations furnished by the Instituto Español de Oceanografia, Madrid, Spain).

Courbes de marée (*a*) pour les 7 et 8 octobre 1983, à Tarifa (trait plein) et à Ceuta (tireté) et (*b*) pendant le mois d'octobre 1983 à Tarifa (documents fournis par l'Institut Espagnol d'Océanographie de Madrid).

The results of these interactions can be seen in the data analyses in Figure 3. Note that at the Spartel Sill, the flow reverses with the tide in the surface layer (*i.e.* at flood, the water in the surface layer moves westward toward the Atlantic Ocean ; conversely, at ebb, the water moves eastward toward the Mediterranean Sea). In the deeper layer, no tide-reversal occurs and the flow is almost always toward the Atlantic.

At Tarifa and further east in the narrower portion of the strait, the surface layer flow is almost always toward the Mediterranean. However, the direction of the deep layer flow alternates with the tide in a fashion similar to (but slower than) the surface layer flow over the Spartel Sill.

The Camarinal Sill is the most crucial impediment to the flow in the region. The bathymetric cross-section at this sill is the smallest in the region (particularly in the deep layer). Thus, all of the flow components increase and the relative effect of the tidal current is at a maximum, particularly in the upper layer. The graph *Ss* in Figure 3 shows that when the tide is at

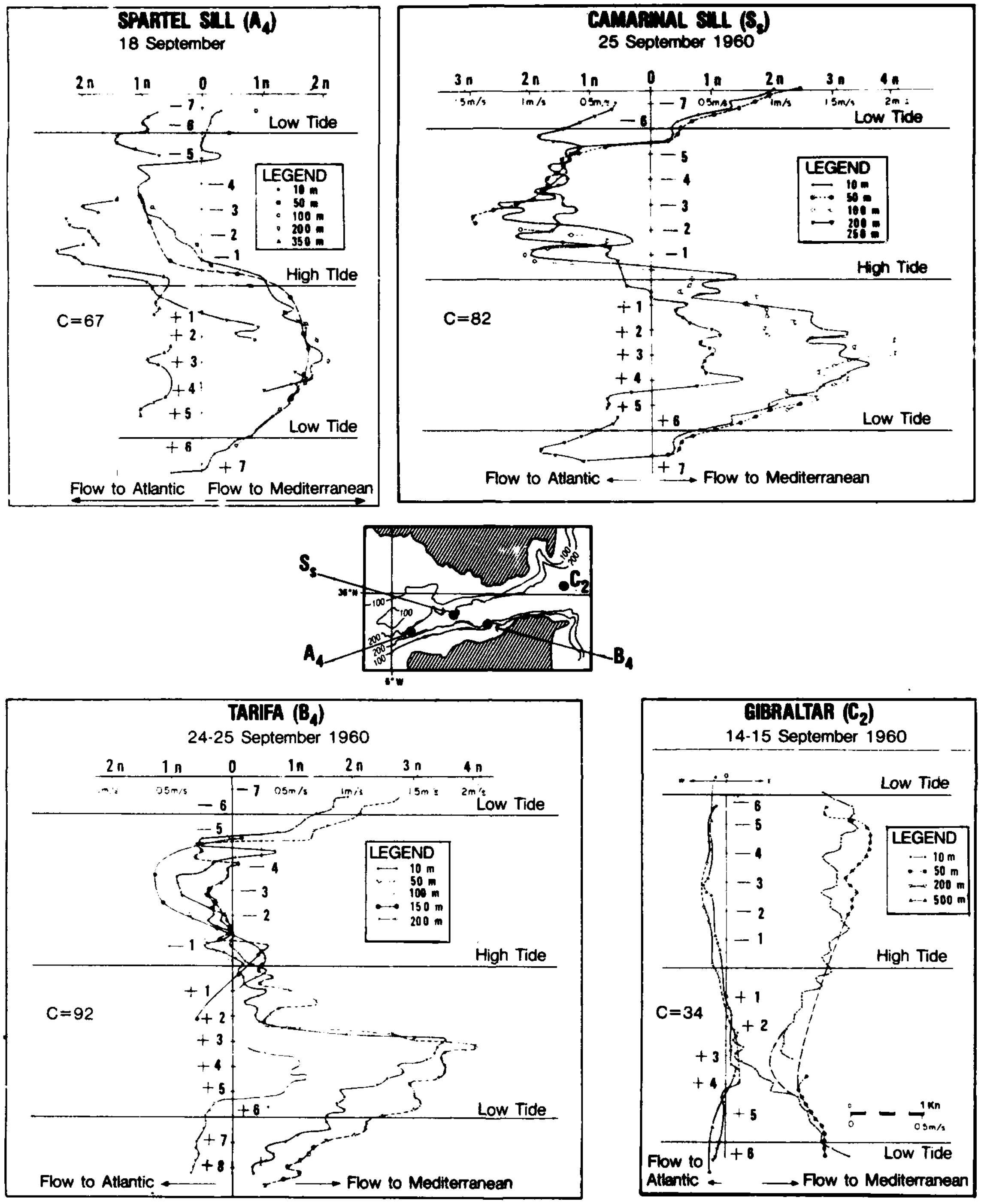


Figure 3

Current changes at different depths during a 12-hour tidal cycle at four positions in the Strait of Gibraltar. On the graphs each curve relates to a particular depth. On the ordinate, time is represented as plus or minus hours from high tide. On the abscissa speed is represented as m/s, *in directions east and west from a null center line (Lacombe* et al., 1964*).*

Changements du courant de marée longitudinal à différentes profondeurs en 4 points de l'axe du détroit. Sur les graphiques, chaque courbe se rapporte à une profondeur déterminée. En ordonnée est indiqué le temps en heures, de 6 heures avant à 6 heures après la pleine mer, soit sur un cycle complet. En abscisse est portée la vitesse en m/s, vers l'Est ou vers l'Ouest par rapport à la ligne 0 (Lacombe *et al.*, 1964).

flood, all of the water in the column moves westward ; when the tide is at ebb, all of the water moves eastward (with the speed decreasing with depth). Thus, at the Camarinal Sill, the current reverses at all depths during the tidal cycle, in contrast with the part tide-reversal/ part steady-flow found at the Spartel Sill, Tarifa, and in the narrower regions of the strait.

In addition to the movements in phase with the semidiurnal tide, violent, small-period flow variations at the Camarinal Sill near the time of high tide seem to generate current and internal wave fronts. Upon generation, these effects propagate eastward and, dominating the surface current regime, can be followed through the strait into the Alboran Sea.

External and internal tides and tidal streams

From Tarifa westward across the two sills, the tidal current has its maximum outflow at about three hours before high tide (or – 3 h) and its maximum inflow at about three hours after high tide (or + 3 h), in phase quadrature, so that the tidal energy flux is small. The tidal currents also show a semidiurnal/diurnal variation. Bryden (pers. comm.) found that the diurnal component was 20 % of the semidiurnal component in his analysis of a two-week current mooring data set taken near the Camarinal sill in 1984.

In the narrow regions of the strait east of Tarifa, the phase relationship between the tide and the tidal current is difficult to assess, and is confused by the increased importance of the diurnal effects (Cavanié, 1973). Here, in comparison to the areas to the west, the Atlantic/Mediterranean interface is generally shallower (shoaling to the east) and the bathymetric sectional area offered to the deep layer flow is larger. The result is a strong near-surface current of Atlantic water almost always set to the east, and moving at supercritical speed (Armi, Farmer, 1985). This lies above the thick, deep layer of Mediterranean water that has a weak, tide-reversing flow.

SHUTTLE AND AIRCRAFT DATA

The Camarinal and Spartel Sills

Surface roughness patterns seen in US space shuttle photographs (Fig. 4) and aircraft XBT, radar, and infrared scanner data indicate that an internal wave was present in the area of the Camarinal Sill during

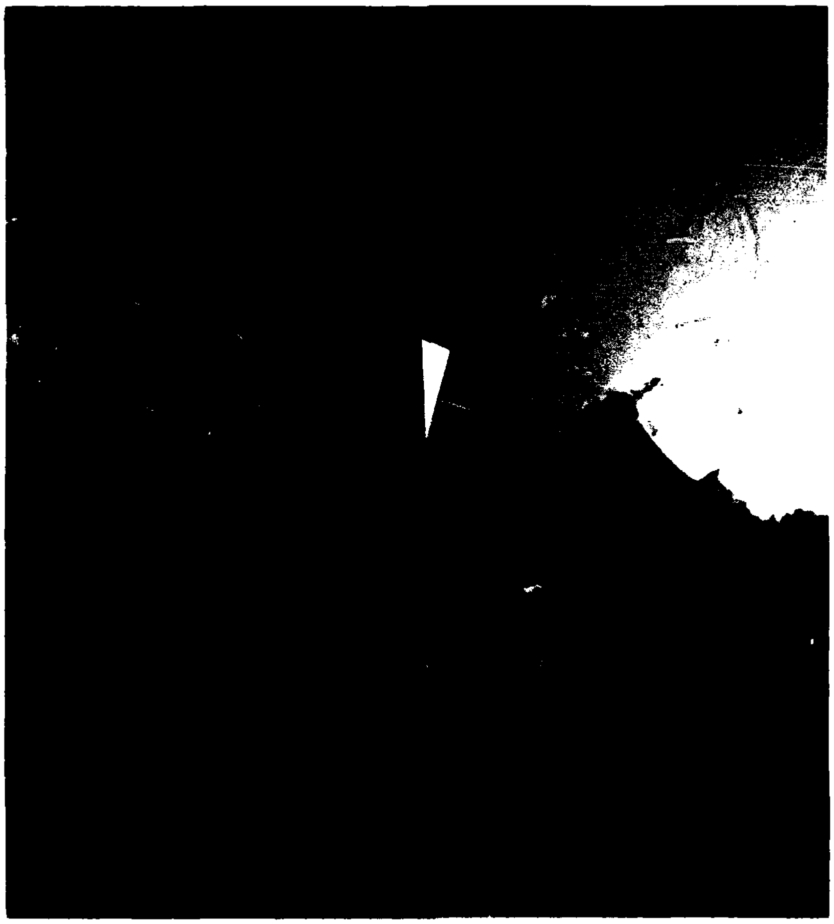


Figure 4

The Strait of Gibraltar as seen from an altitude of 198 km *by the US space shuttle crew of Mission* 41-*G on* 12 *October* 1984. *The photograph shows the noon sun reflecting off variations in roughness of the ocean surface (very little of the photograph contains clouds). In the photograph, the most prominent roughness features are those seen bowing eastward into the Mediterranean Sea. These features are the surface manifestations of a packet of ten or more progressive internal waves.*

At the western side of the strait a slightly more subdued region of reflection shows the area of the standing internal wave two hours before high tide. It shoud be emphasized that the internal waves have very small surface amplitude, and that the brighter reflections come from disturbed (and thus more reflective) water that comprises the rip area (NASA photograph 40 050*).*

Le détroit de Gibraltar vu d'une altitude de 198 km par l'équipage de la mission 41-G de la navette spatiale américaine, le 12 octobre 1984. La photographie montre le soleil de midi renvoyant par réflexion les variations de rugosité de la surface océanique (seule une petite partie du cliché comporte des nuages). Sur la photographie les traces de rugosité les plus notables sont celles que l'on voit s'incurvant vers l'Est en direction de la Méditerranée. Ces traits sont les manifestations superficielles d'un groupe d'au moins une dizaine d'ondes internes en progression.

Du côté ouest du détroit, une région de réflexion plus discrète indique la zone de l'onde interne stationnaire deux heures avant la pleine mer. Nous insistons sur le fait que les ondes internes ne suscitent en surface qu'une très petite variation de niveau, et il est vraisemblable que les réflexions les plus brillantes proviennent de l'eau agitée (et donc plus réfléchissante) comprise dans la région des remous (cliché de la NASA, 40 050).

the period 6-11 October 1984 (La Violette, Arnone, 1985). In comparing the October 1984 data with historical data, La Violette and Arnone (1985) suggested that the internal wave is a permanent feature of the waters over the Camarinal Sill. They stated that the region's periodic surface roughness and subsurface changes were probably manifestations of tide-related changes in the direction and flow of the Atlantic and Mediterranean water masses as these move over the sill.

Recent helicopter flights (October, 1985) were made over the strait by one of the authors (P. L.) at the times of spring and neap tide. These disclosed that predominant surface roughness patterns were present over the sill during spring tide, but that no distinct pattern was noticeable during neap tide. XBTs dropped during phases of the spring tide showed the rise and subsidence of the internal wave with the tide. Unfortunatly, because of problems with the radar used for accurate navigation, no XBT was dropped during the neap tide. Thus, although the lack of surface roughness patterns indicate the internal wave over the sill to be more subdued during neap tide then during spring tide, no subsurface data is available.

The helicopter also flew over the Spartel Sill during spring tide (but did not drop XBTs). These flights showed roughness patterns indicative of a small packet (three or four) of internal waves present in the area of the sill. These roughness features were poorly-defined in comparison to similar features noticed east of the Camarinal Sill. No feature was noticed during neap tide.

The narrows of the strait

During these same series of helicopter flights, XBTs were dropped over a complete tide cycle along a north/south line from Point Cirus to the coast of Spain. The complete drop along the line, consisting of seven XBTs each spaced approximatly 1.5 km apart, took an average of 30 min to complete. The drops were made every three hours : at low, flood, high and ebb phases of the tide.

Analyses of the Point Cirus/Spain XBT data showed that the depth of the 14 °C isotherm was closer to the surface in the northern part of the strait. In general, the isotherms across the strait moved up and down in phase with the tide. The 14 °C isotherm became shallower during flood and reached a minimum depth at high tide. As the cooler water surfaces, a surface thermal gradient of two degrees (19/20 °C) was displaced toward Morocco, occupying one half of the strait at high tide. As the tide ebbed, the gradient returned northward. An uncalibrated thermal scanner flown the following day indicated that the 19/20 °C thermal gradient may have been part of an East/West thermal gradient line that stretched from Gibraltar to the Camarinal Sill.

Although these are temperature rather than salinity data, the authors feel that the tide-related movement of the isotherms discussed above reflect changes in the Atlantic/Mediterranean interface. Other data containing both temperature and salinity show changes similarly related to the tide and interface depth variations. Examples of these changes are presented below.

SHIP DATA

Data

Current measurements were made in the strait in 1960 (Fig. 3 and 5, left) and internal wave measurements in May 1967 (Fig. 5, right). Temperature and salinity profiles were also made over the Camarinal Sill (Fig. 6 and 7 here and *see* Fig. 17, *a, b, in* Lacombe, Richez, 1982). These data show that the tidal phase/interface depth relationship revealed by the helicopter XBT data is also found in the ship data. For example Figure 5, right, shows that the interface depth as defined by salinity is at its minimum at high tide and at its maximum at low tide. In addition, the salinity presentations for neap and spring tide in Figure 7 indicate that the magnitude of these variations vary with the lunar phase of the tide.

The periodic events at the Camarinal Sill

According to the records of one of the authors (H. L.), two North-South oriented parallel lines (2 000 m apart) of choppy water were noted east and west of the anchored *Calypso* on 25 September 1960 from the position *Ss* in Figure 3. These lines were similar to the surface roughness patterns photographed from the aircraft in October 1984 and appear to be similar to reports made by ship captains in the same region (*e.g.* Mariner Observer, 1928 ; 1938 ; 1948).

The 1960 observations noted that the lines remained in place and 2 000 m apart from about – 5 h 00 to – 0 h 45. During this time the flow in the surface layer was west toward the Atlantic, at about 1 m/s. Eddies were seen to form – 3 h and – 2 h 40. At – 0 h 40, the two lines rapidly merged together and disappeared amid violently moving eddies.

Figure 3 shows that sharp changes in current speed (and direction) over the sill also occurred at this time. At – 0 h 35, the current abruptly veered from flowing westward toward the Atlantic to eastward to the Mediterranean, reaching 0.5 m/s at high tide. A second strong increase of about 1 m/s took place at + 1 h. The visual observations noted that lines of eddies were seen moving east, at + 0 h 55, + 1 h 10, and + 1 h 15. With the coming of night, no further visual observations could be made.

Figure 3 indicates that for about five hours between low and high tide, the flow drives all of the water directly east of the sill up and over the sill. As the deeper (and colder) waters are pressed against the rising eastern slope of the sill, they are buoyed upward, forcing the waters above them also to rise, eventually broaching the surface. The two lines of choppy water 2 000 m apart noted during this time of the tide by the *Calypso*, and figuring prominantly in the helicopter, aircraft, and mariner's reports may be due to this general upward movement.

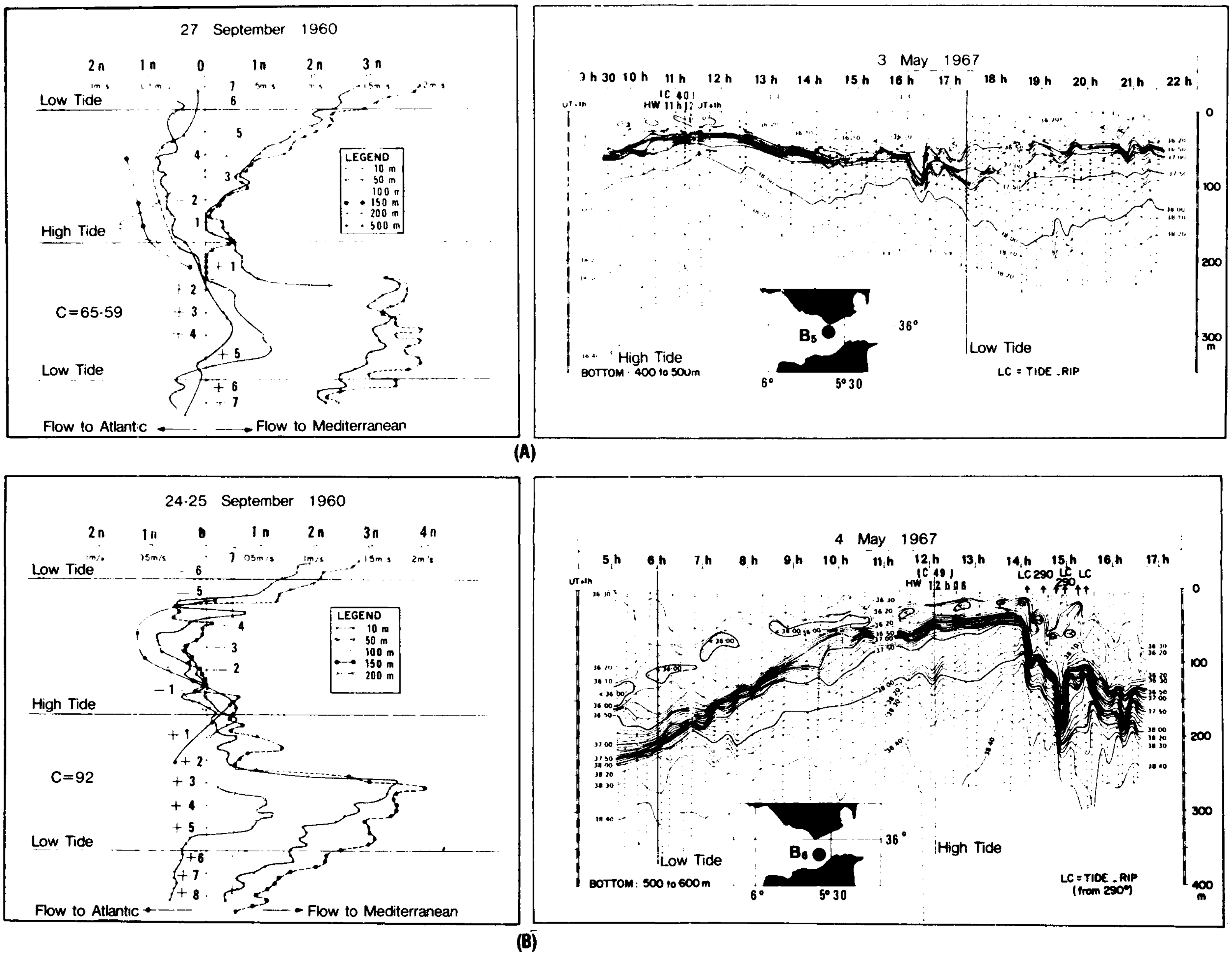


Figure 5

Tidal current speed and direction variations and salinity depth variations for a north and south point in the Strait of Gibraltar (from Calypso, 1960 *and* J. Charcot, 1967*). The current graphs are arranged similar to Figure 3. The abscissa of the salinity graphs is a time presentation arranged in units of hours (after Lacombe, Richez, 1982 ; 1984).*

Vitesse du courant de marée longitudinal aux points B' 2 et B4 (*Calypso*, 1960) et ondes internes de salinité aux points proches B5 et B6 des 3 et 4 mai 1967 (*J. Charcot*). La présentation des courbes de courants est identique à celle de la figure 3. L'abscisse des courbes de salinité représente le temps en heures (d'après Lacombe, Richez, 1982 ; 1984).

Surface layer axial divergence of flow during flood

The data analysis in Figure 6 suggests that the maximum height of the tide coincides with the sharp decrease of the westerly flow as well as with the maximum lifting of the interface. A divergence in the surface layer between the area of the sill and the longitude of Tarifa may be related to the vertical rise of the interface during the period of flood.

This divergence may be seen in an examination of Figures 3 and 5, left. Note that during the period of flood, the current at the surface layer at the sill is strongly westward (Fig. 3). However, during this phase of the tide, at Tarifa the flow is strongly eastward (Fig. 5 A, left) or only slightly westward (Fig. 5 B, left). The divergence is limited to the surface layer. In the deep layer, from – 4 h to – 1 h, the flow at both the sill and Tarifa is set strongly to the west.

The axial divergence of flow above the interface is consistent with several simultaneous regional events: upward movement of the interface; cooling at the surface (Fig. 6), and a large increase in the volume of Mediterranean water in the sill area. In addition, as the current in the surface layer east of Tarifa is almost always toward the Mediterranean, there is no westward return flow of Atlantic water from this region. This lack of return flow during flood implies that the comparatively small amount of low-salinity water flowing westward in the upper layer over the sill during flood, must come from convergent flows of Atlantic water. Source regions for this are probably the shallow area along the Spanish coast northwest of Tarifa and the Moroccan coast area. Indications that this is true can be seen in the NOAA satellite data in next section, below.

Abrupt upheavals of the interface over the Camarinal Sill during flood

During some tides, between – 3 h and – 0 h 30 (*see* Fig. 6 here and Fig. 17 *b* of Lacombe, Richez, 1982), one or several abrupt upheavals of the interface take place. As the current then is strongly westward, these upheavals correspond to excesses of Mediterranean water outflow: it may be asked whether these upheavals are a natural means of "exporting" any excess flow of this water, due to non-tidal causes, to the west. Conversely, the sudden deepening of the interface at about high-water increases the Atlantic inflow.

What rôle does the strong westward flow moving up the eastern slope of the Camarinal Sill play in the amplitude of the internal wave there? Do the abrupt upheavals or deeepening of the interface factors tend to "absorb" variations of the flows in the two layers due to external causes?

NOAA SATELLITE DATA

NOAA data

If, as the aircraft and ship data indicate, the Atlantic water/Mediterranean water interface is closer to the surface between – 3 h and + 3 h, the surface water should then be cooler than during the rest of the cycle for, at these times of the year, the incoming Atlantic water is markedly warmer than the outgoing Mediterranean water. Therefore, satellite thermal imagery should show cooler temperatures in the strait indicative of the nearness of the interface to the surface from – 3 h to + 3 h.

In addition, the axial-divergent/side-convergent flow in the surface layer suggested in the ship data should also be detectable in the thermal patterns displayed in the satellite imagery. In turn, the changes in the thermal patterns in relation to the tidal phase could give a horizontal dimension to the ship's point measurements.

There is no present satellite sensor with sufficient resolution to monitor a single twelve-hour tidal cycle

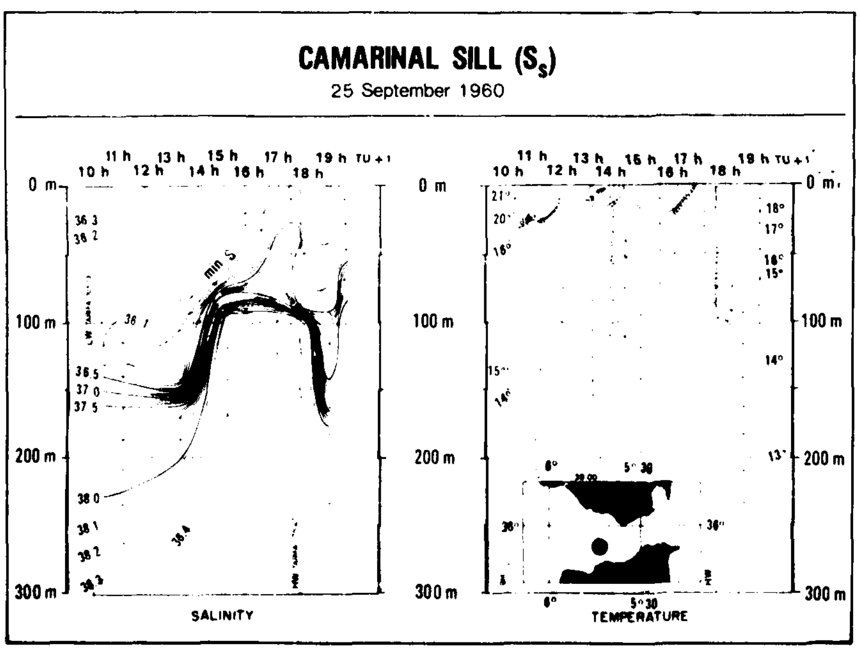


Figure 6
Salinity and temperature depth variations at the deepest point on the Camarinal Sill (S), September 25, 1960 (Lacombe et al., *1964).*

Onde interne de salinité et de température au point le plus profond du seuil de Camarinal (*S*), 25 septembre 1960, *Calypso* (Lacombe *et al.*, 1964).

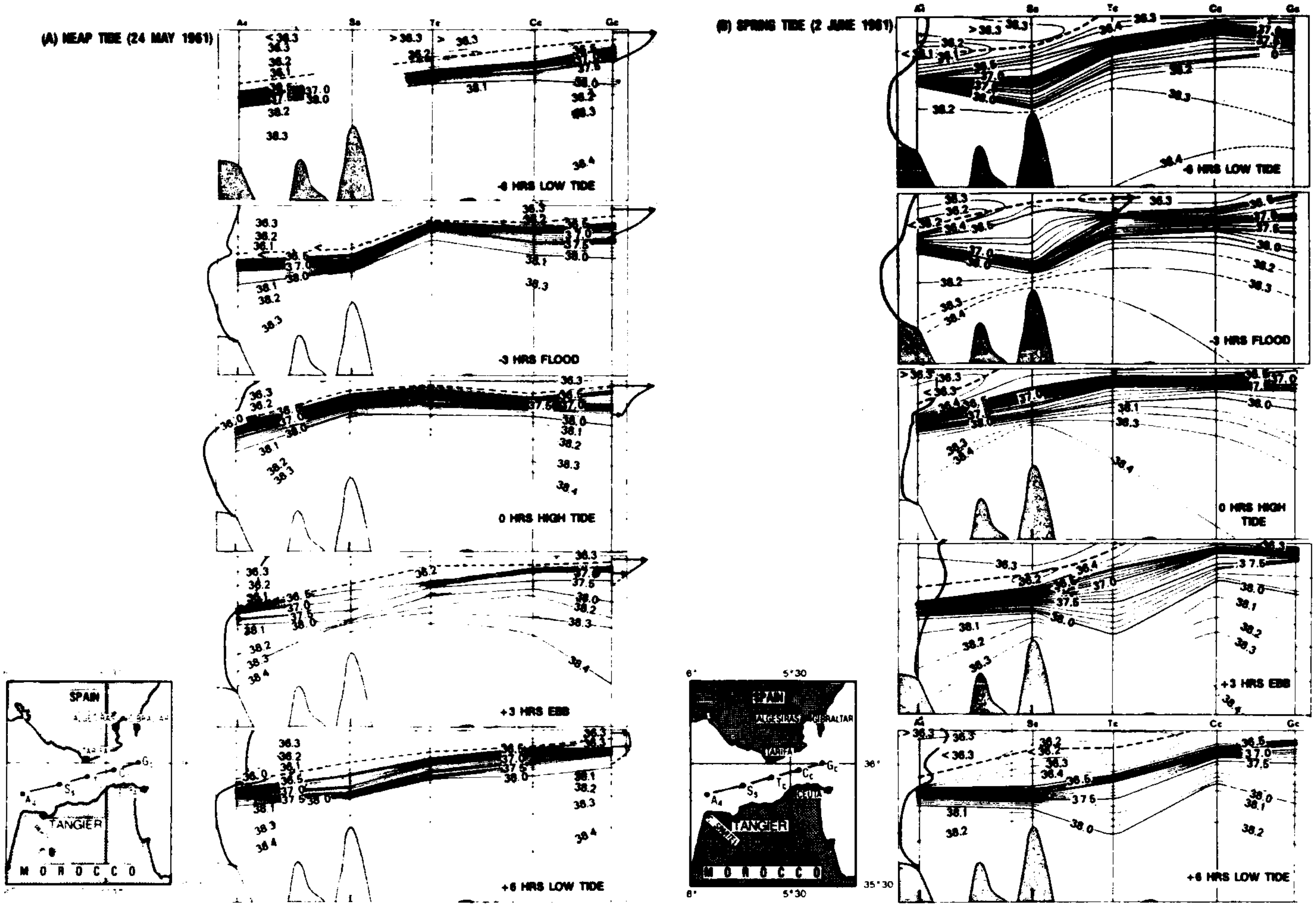


Figure 7

Salinity depth variations along the axis of the Strait of Gibraltar over a tidal cycle at neap tide with C = 42 and spring tide with C = 89. Dashed lines refer to area of minimum salinity (after Lacombe, Richez, 1984).

Variations longitudinales de la profondeur des isohalines pendant un cycle de marée de morte-eau (C = 42) le 24 mai 1961 et de vive-eau (C = 89) le 2 juin 1961. Les tiretés indiquent la zone du minimum de salinité (d'après Lacombe, Richez, 1984).

(Meteosat has a resolution of 7 km in the latitude of the strait). Because of this, an artificial representative tide cycle was constructed using afternoon NOAA 7 infrared data for the period 6-16 October 1982. These data were processed into geometrically-registered and atmospherically-corrected thermal imagery ; *i.e.* all the images were processed to the same map projection (Mercator) and to display gray-tones representative of absolute temperatures. Ship data for the period show that Atlantic water was approximately 18 °C, and that Mediterranean water approximately 13 °C (all NOAA data used in this study were provided by the Centre de Météorologie Spatiale, Lannion, France. Processing was done at NORDA, Bay St. Louis, Mississippi, USA).

The construction of an artificial tidal cycle was made possible by the fact that a different phase of the tide was present at the time of each day's afternoon satellite pass. Thus, each day's image could be used to represent a specific phase (or hour) of the tide. The imagery in the order of the constructed tidal cycle is shown in Figures 8 and 9.

The NOAA 7 passes for 9 and 8 October 1982 occur close to the same phase of the tide (– 3 h 20 for 9 October and – 3 h 30 for 8 October). The 8 October pass was arbitrarily selected for use in the constructed tide sequence. Both images, however, showed the same thermal conditions and either could have been used in the construction.

Because of clouds, no afternoon image is available for either 14 or 15 October 1982. For completeness, a morning image (~ 03.00 GMT) is included that shows surface temperatures approximately 1 °C cooler than the afternoon imagery. Because of the effects of diurnal cooling, mostly afternoon imagery were used in the constructed tide cycle.

Constructed tide cycle imagery

In Figure 8, at just about low tide (actually – 5 h 15 in the tide cycles of 10 October), the surface thermal features in the strait are shown to be uniformly cool with some cold water on the Spanish side of the strait.

Flow measurements cannot be made using this set of imagery. However, the presence of the same temperature water in the Atlantic to the west and cooler water

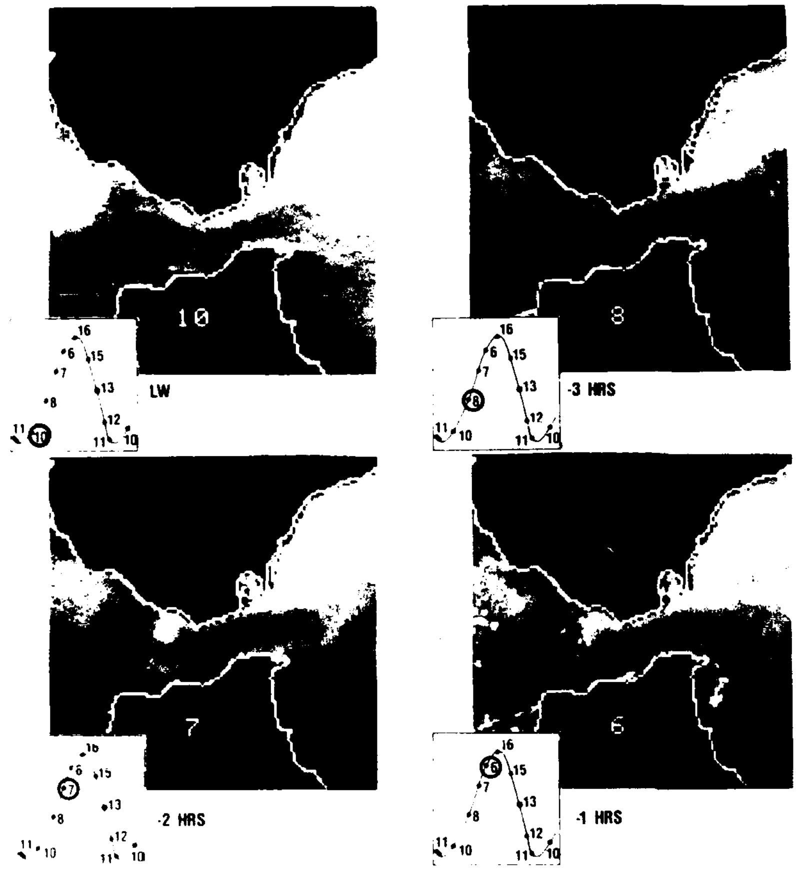


Figure 8

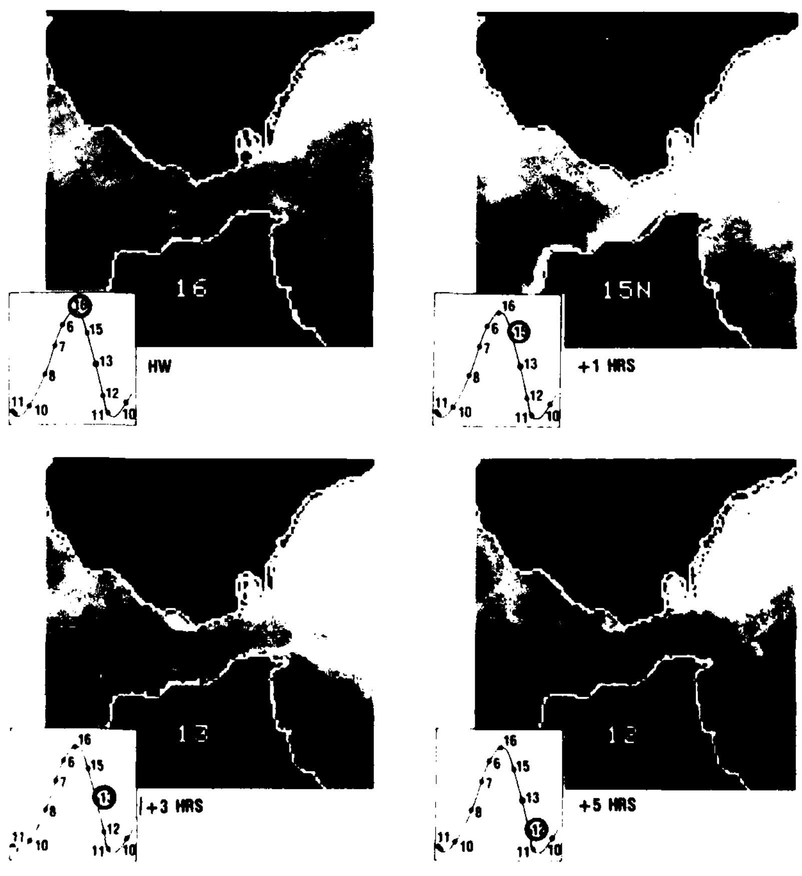
Satellite-derived surface thermal pattern variation in the Strait of Gibraltar over a constructed tidal period for the period of low to high tide (from October 1982 satellite data provided by the Centre de Météorologie Spatiale, Lannion. Numbers refer to the dates of each afternoon pass).

Distribution des variations thermiques de surface dans le détroit de Gibraltar, d'après des vues-satellite, pour un cycle de marée reconstitué depuis la basse mer jusqu'à la pleine mer (données de satellite provenant du Centre de Météorologie Spatiale de Lannion pour octobre 1982. Les nombres se rapportent aux dates des passages d'après-midi).

Figure 9

Satellite-derived surface thermal pattern variation in the Strait of Gibraltar over a constructed tidal period for the period of high to low tide (from October 1982 satellite data provided by the Centre de Météorologie Spatiale, Lannion. Numbers refer to the dates of each afternoon pass).

Distribution des variations thermiques de surface dans le détroit de Gibraltar, d'après des vues-satellite, pour un cycle de marée reconstitué depuis la pleine mer jusqu'à la basse mer (données de satellite provenant du Centre de Météorologie Spatiale de Lannion pour octobre 1982. Les nombres se rapportent aux dates des passages d'après-midi).



in the Mediterranean to the east indicates that the cool surface water in the strait is probably Atlantic water moving eastward. According to the 1960 ship data, the flow in the strait at this time of the tide is generally eastward. The same data indicate that speeds are probably less than 0.25 m/s at the sills and greater than 0.5 m/s at Tarifa and Gibraltar.

As the tide starts to flood, the surface thermal patterns of the strait change, reflecting corresponding changes in the flow in the surface layer. At − 3 h (8 October), the water in the central channel of the strait is probably still Atlantic water.

Now, indications of divergent flow appear, as cold tongues of water extend from both the Spanish and Moroccan coasts between Tarifa and the Camarinal Sill. The ship data indicate that at this time of the tide, there is a strong westward flow over the sills with a speed of almost 1 m/s over the Camarinal Sill. Conversely, the flow at Tarifa is less than 0.4 m/s to the east on the Spanish side and 0.25 m/s to the west on the Moroccan side (Fig. 5). Note that the ship's position on the southern side of the strait is in the southern cold tongue. This is the first indication of convergent flow toward the Camarinal Sill.

At − 2 h and − 1 h (7 and 6 October), the tongues become more pronounced, almost (but not quite) closing the strait with a band of cold water. The central core of Atlantic water lying along the axis of the Strait remains in position. The ship data indicate that a strong westward flow exists over the sills, with a flow of approximately 0.2 m/s on the southern portion of the strait opposite Tarifa (the northern side shows only a slight eastern current of less than 0.1 m/s). At Gibraltar the eastern flow continues in the surface layer.

At high tide and at + 1 h (16 and 15 October, in Fig. 9), the strait still shows evidence of divergent flow. This conflicts with the ship data that at + 1 h show uniformly eastward flow throughout the strait : 0.5 m/s east flow at the sill and 0.5 m/s (north) and 0.2 m/s (south) at Tarifa. It is interesting that when slightly after + 2 h, the eastward flow increases dramatically at these locations (Camarinal Sill, 1.5 m/s ; Tarifa (north), 1.7 m/s ; Tarifa (south), 1 m/s), the imagery also show a sharp corresponding change.

Now, for the period of ebb (13 and 12 October), the imagery show evidence of a strong influx of warm Atlantic water in the strait. This is seen best in the 12 October image (for purposes of comparison, this 12 October image may be set against that which is best representative of flood conditions : 6 October, in Fig. 8). The increased amount of warmer temperatures in the strait with the withdrawals of the cold tongues indicate the dominance of Atlantic water in the Strait and the cessation of the divergent flow.

Thus, the surface thermal conditions in the imagery indicate the same interface depth/tide phase relationship as the aircraft and ship data (*i.e.* from − 3 h to + 3 h, generally cool surface water, indicating a shallow interface ; from + 3 h to − 3 h, generally warm surface water, indicating a deep interface). They also show strong evidence of the divergence present during flood between the Camarinal Sill and Tarifa, as well as the convergence of water from the coast toward the central portion of the strait.

This sequence of satellite images was chosen because they comprised the only satellite data of sufficient temporal length available that showed the strait cloud-free. The fact that the limited data set showed the thermal changes as expected gives credence to the theories presented of the tide period/interface depth and divergence/convergence relationship. Note that since the surface thermal conditions shown by each image formed part of the actual tidal conditions during that day, the conditions depicted in the constructed tide were actually repeated on each of the eleven days.

In an effort to expand this limited data set, 13 cloud-free, randomly selected NOAA images of the strait for the period June through October 1982 were examined. These showed the same thermal patterns/tidal phase relationship as the imagery presented here.

THE DESCRIPTIVE MODEL

Conditions for the model

Based on the above data, a descriptive model of events in the strait can be constructed. The occurrence of certain conditions, as set out below, on the Camarinal Sill is basic to the descriptive model :

1) maximum value of the tidal stream modulus, in both the upper and deeper layers ;

2) predominance of these tidal streams with respect to the mean flows ;

3) maximum height of the internal wave in comparison with the rest of the strait, reaching as much as 2/3 of the total depth ;

4) simultaneous occurrence of the maximum tidal stream and the maximum depth variation of the internal wave (phase quadrature) for the semidiurnal component. That is, the maximum current (in either direction) takes place at the time when the semidiurnal component of the interface is at its mean depth. This relative phase tends to introduce symmetry in the Atlantic and Mediterranean flow exchange on the sill.

Thus, the emission of Atlantic water toward the east and of Mediterranean water toward the west occur as large " tidal pulses ", with the Mediterranean water pulse flowing out during flood and the Atlantic water pulse flowing in during ebb. These pulses have their greatest volume during spring tides.

As mentioned in a preceding section (" Ship data "), during some tides, between − 3 h and − 0 h 30, abrupt variations in the strong westward flow moving up the eastern slope of the Camarinal Sill appear to create upheavals of the interface. These effects seem to generate current and internal wave fronts. Both effects propagate eastward and, dominating the surface current regime, move through the strait into the Alboran Sea.

The tidal cycle descriptive model

Using the ship data as a frame (Fig. 10), the descriptive model of flow conditions during a typical tidal cycle can be presented as follows :

Low tide (– 6 h)

The current during this phase of the tide has started to reverse at the sills and at Tarifa and is generally small. The interface is at its lower level. The Atlantic water pulse from the previous tide has ended and the outflow tidal pulse begins.

Mid-flood tide (– 3 h)

This is the time of the maximum outward flow over both sills and the maximum amount of Mediterranean water is emitted from the strait. Now, the divergence in the surface layer, between the Camarinal Sill and the Tarifa section, is strongest, signalling a complete interruption of the eastern flow of Atlantic water through the strait. The flow in the surface of the narrow area of the strait continues eastward, carrying the residue of Atlantic water from the previous tide. This is the midpoint in the ascent of the interface in the strait.

At the Camarinal Sill, very sharp and irregular ascents of the interface occur, as well as strong variations in the tidal current. At times these abrupt ascents sharply increase the amount of Mediterranean water going over the sill. If this occurs at a time when the outflow current is still strong, a greater than normal pulse of Mediterranean water will flow into the Atlantic.

High tide (HW)

The tidal current has reversed and the inward tidal pulse begins. The interface is at its shallowest in the tidal cycle. At the Camarinal Sill, a rapid deepening of the interface (sometimes abruptly) occurs, together with a very strong increase of current to the east (with abrupt fluctuations).

Mid-ebb tide (+ 3 h)

The inward flow is now at its maximum in the Mediterranean as well as in the Atlantic layers. The tidal component of the interface depth has reached its mid-depth position. Now, there is no divergence zone between the Camarinal Sill and the Tarifa section ; and Atlantic water flowing eastward as a strong pulse through the whole strait is at a maximum.

The interruption at + 1 h of westward flow in the lower layer means that no or very little Mediterranean water is leaving the strait. Thus, this period marks an end to the Mediterranean water pulse till + 4 h 30. The flow of Atlantic water will continue to be strong until – 6 h when the reverse of the tidal stream will restore the zone of divergence and mark the end of the Atlantic water pulse.

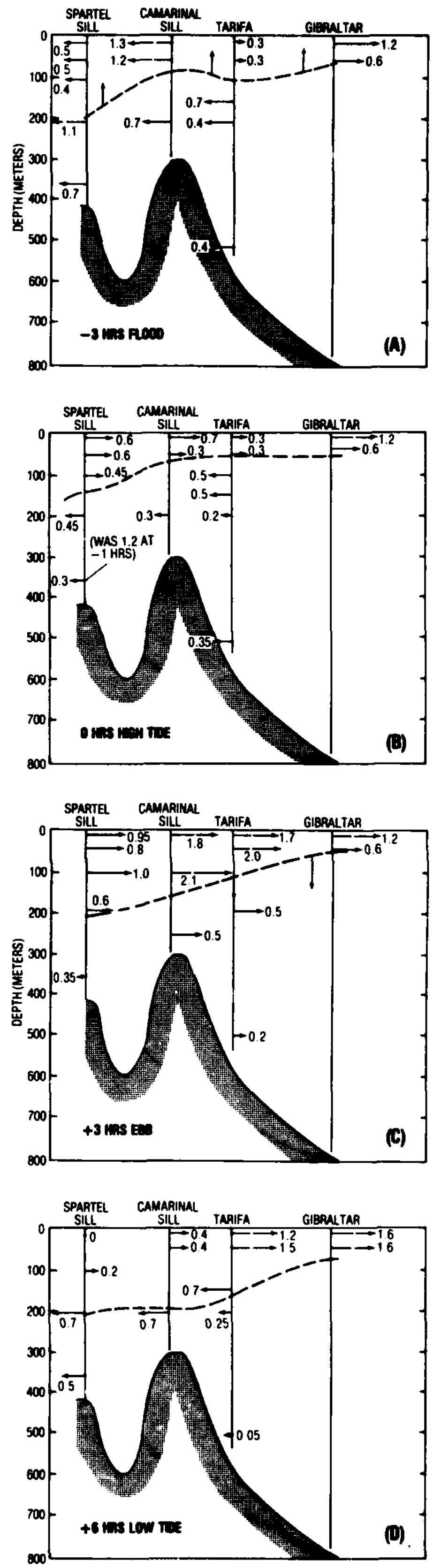


Figure 10

Tidal current speed and direction variations with depth along the axis of the Strait of Gibraltar for a constructed tide cycle. The dashed line represents the depth of the Atlantic water/Mediterranean water interface (from September 1960 *ship data).*

Variations en fonction de la profondeur de la vitesse et de la direction des courants de marée le long de l'axe du détroit de Gibraltar, pour un cycle de marée reconstitué. La ligne en tiretés représente la profondeur de l'interface entre eau atlantique et eau méditerranéenne (données de septembre 1960, *Calypso*).

TIDAL CURRENT AND INTERNAL WAVE-FRONTS EAST OF THE SILL

The passage of the pulses and the movement of the progressive internal waves through the strait appear to have a close association, which deserves brief mention as part of the present discussion.

Progressive internal waves in the Strait of Gibraltar have long been a subject of study (*e.g.* Jacobsen, Thompsen, 1934 ; Lacombe *et al.*, 1964 ; Cavanié, 1972 ; Boyce, 1975 ; Lacombe, Richez, 1982 ; Kinder, 1984 ; La Violette *et al.*, 1986). These studies indicate that the waves usually occur in groups, or " packets " and that the waves are generated at, or near, the Camarinal Sill just prior to high tide. Examples of the internal waves are prominent in the shuttle photographs (Fig. 4) and in the analyses of the data collected in the multiple-ship surveys (*e.g.* Fig. 5 and 6).

The model presented above suggests that the time of high water marks two simultaneous events on the Camarinal Sill : one is the sharp depression of the interface ; the other is the generation of a current front. Both features propagate eastward at apparently the same speed. However, the depression is propagated as an internal wave packet, while the current front, very sharp in Tarifa section, is smo[illegible] more to the east. The series of depressions that mark the eastward progress of the internal waves are easily noted in the water column data.

The speed of the internal waves within the strait vary (Table) : Cavanié (1972) showed an internal wave front arriving off Gibraltar about 7.5 hours after high tide for one semidiurnal tide and about 3.5 hours after high tide of the subsequent semidiurnal tide. In their study, La Violette *et al.* (1986) also noted that the wave packets arrived at Gibraltar at different phases of the semidiurnal tide. Both nighttime packets arrived at Gibraltar 1 to 2 hours after low tide, while the morning packet arrived 1 to 2 hours before low tide. They suggest that, because of the match in the phase times of the two nighttime packets, the different arrival times were caused by the variation in strength of the semidiurnal tidal current.

Thus, the speed of the internal wave packets moving through the strait varies according to the strength of the tidal current. The study presented here suggests that in a similar fashion, the degree of vertical movement of the Atlantic/Mediterranean interface also depends on the strength of the tidal currents. The data indicate that the start of a wave packet at the Camarinal Sill and the shallowest depth of the interface occur at the same time : at around high tide. However, as the wave packet moves east through the strait, its position in the interface depth variation at a given point will vary according to the tidal strength.

The study by La Violette *et al.* (1986) is a good example. In their study, the passage by Gibraltar of one set of waves occurred two hours prior to low tide (or two hours prior to maximum interface depth), whereas the nighttime packet passed by two hours after low tide (or two hours after maximum depth). Thus, according to the distance from the Camarinal Sill and the strength of the tidal current, the internal waves may be found impinged at any point of the interface, whether deep or shallow such as in the temporal diagrams in Figures 5.

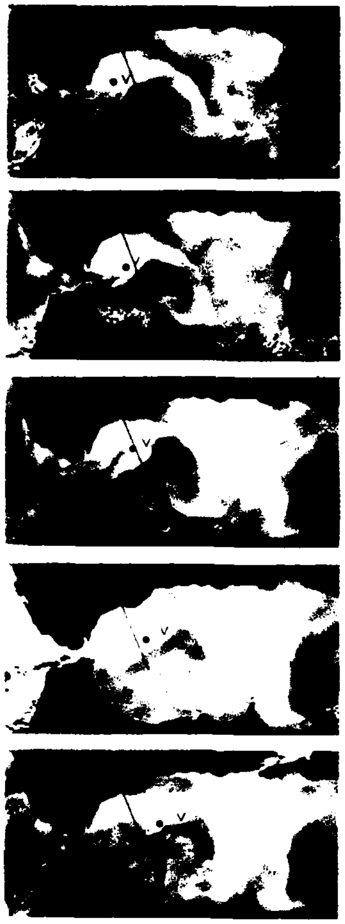
EVIDENCE OF TIDAL-RELATED PULSE-EMITING FROM THE STRAIT

The cyclic emissions of Atlantic water from the eastern end of the strait into the Alboran Sea may have been indirectly noted by La Violette (1984). This study, based mainly on satellite thermal imagery, concentrated on the presence of cold water features periodically found at the eastern end of the strait. These appeared to move away from the strait and rotate about the Alboran Sea Gyre (Fig. 11). This

Table
Measurements of phase speeds of internal waves and current-fronts in the Strait of Gibraltar.
Mesures de vitesses de phase des ondes internes et des fronts de courants dans le détroit de Gibraltar.

Frassetto (1964)	1.3 knots (0.7 m/s)	
	4.0 knots (2.0 m/s)	
	4.4 knots (2.2 m/s)	
Ziegenbein (1970) *	3.1 knots (1.6 m/s)	
	4.3 knots (2.2 m/s)	
	5.0 knots (2.6 m/s)	
	2.3 knots (1.2 m/s)	
	3.1 knots (1.6 m/s)	
Cavanié (1972)	3.5 knots (1.8 m/s)	
	4.3 knots (2.2 m/s)	
	3.8 knots (1.9 m/s)	
	3.8 knots (1.9 m/s)	
Lacombe and Richez (1982)	4.3 knots (2.2 m/s)	mean value Camarinal Sill-Tarifa
	3.2 knots (1.6 m/s)	locally B6
	5.0 knots (2.6 m/s)	Camarinal Sill-Ceuta
La Violette *et al.* (1986)	2.1 knots (2.1 m/s)	

* Individual waves measured between thermistor chain moorings. Speeds may be inflated if moorings were not orthogonal to waves.



1432 GMT OCTOBER 6

0256 GMT OCTOBER 7

1422 GMT OCTOBER 7

0244 GMT OCTOBER 8

1408 GMT OCTOBER 8

Figure 11

Cyclic emission of cold water features from the eastern end of the Strait of Gibraltar and their rotation about the Alboran gyre (La Violette, 1984).

Émission cyclique de taches d'eau froide à partir de l'extrémité orientale du détroit et leur rotation autour de la Mer d'Alboran (La Violette, 1984).

cold water is probably water that had upwelled between the times of warm Atlantic water pulses.

Since the satellite imagery provides no salinity information and since the temperature of the warm Atlantic water was close to that of the warm water found in the centre of the Alboran Sea Gyre, no differentiation between the two water masses could be detected in the satellite thermal imagery. Hence, the emphasis on the more prominent cold water features in the La Violette (1984) study.

A comparison of the model presented above and the results of La Violette (1984) suggests that the Atlantic water pulses are interposed between the cold water features. It may be further inferred that the Atlantic water pulses, upon leaving the strait, become caught up in the rotation of the Alboran Sea Gyre and, as they circle the Alboran Sea, mix and eventually form the bases of the surface water mixture found in the centre of the Alboran Sea Gyre.

Pulse emissions of the deeper Mediterranean water from the western side of the strait have not been detected. As the model suggests, the strength of the Mediterranean emissions should vary biweekly ; being stronger at the spring phase of the tide than at the neap. The possibility of these deep pulsic emissions (including the variability of their strength) should be considered in any study of the spreading of this dense water mass.

CONCLUSIONS AND REMARKS

Conclusions

This study of shuttle, aircraft and ship data shows the flow in the strait of Gibraltar. The data used are scattered in time and are of short duration. However, we believe the repetition of the events shown in the different data to indicate that these events represent normal conditions. The study shows that the emission of Atlantic water towards the east end of Mediterranean water towards the west occur as tide-related pulses. It indicates that the Camarinal Sill and the Tarifa section play key roles in the producing of these events. Periodic events occur at two time scales :

1) For the semidiurnal tidal period, the largest amount of Mediterranean water flows out of the strait into the Atlantic during the flood phase of the tide ; and the largest amount of Atlantic water flows through the strait during ebb. These flows occur as large, semidiurnal pulses with the highest volume and speed values occurring about mid-tide (external and internal). The values found in these large pulses are much larger than the values of the mean flows in and out of the strait and are greatest during spring tide ;

2) At the Camarinal Sill, over much shorter periods (of the order of 15 min to 1 h) complex hydraulic, non-linear phenomena of unknown origin generate very abrupt changes during the later period of flood in the near-surface current and interface depth. These abrupt events not only appear to interact with the semidiurnal pulses, but generate an internal wave- and current-front which, during flood, propagate eastwards into the Alboran Sea. These short period fronts are not locked in phase with the surface and internal semidiurnal tides ; yet they dominate the internal wave amplitude and current regime in the surface layer east of the sill.

The importance of the sill may result in part from events occurring at the sections at and east of Tarifa. We have shown that east of Tarifa, the surface layer current always sets eastward, often at supercritical speed over an eastward shoaling interface. Thus from this region there is almost no westward flowing Atlantic water. As there is westward flowing surface layer water over the Camarinal Sill during flood, a convergence flow must be generated at this time to supply this surface layer of water. Ship and NOAA data suggest this source is the Spanish coast just west of Tarifa and from the Moroccan coast.

Remarks

What causes the divergence of Atlantic water, or the important shoaling of the interface in the narrows of the strait ? Are these the result of the supercritical flow ? As these phenomena appear to have a very significant bearing on the regime in the strait, it is important to understand their causes.

Furthermore, we know little about what happens just west of the sill, or about the generation of the short-period fluctuations of current, during mid- to late-flood, that modulates the very abrupt reversal of the tidal stream from west to east. The presence of these strong, short-period fluctuations may play a rôle in generating the internal wave front and the current front which propagate to the east, particularly in the southern half of the Tarifa section.

In our view, the fact that the current in the surface layer in the Strait east of Tarifa is always flowing east, and that there is no outflow of Atlantic water in the narrowest part of the Strait, is important. The consequences of this observed fact for a fuller understanding of the physical events within the strait deserve investigation.

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